Journal of Cleaner Production 212 (2019) 70–80

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

How nonlinear control can enhance the automobile efficiency and reduce harmful emissions: China case study

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ARTICLE INFO

Article history:
Received 6 May 2017
Received in revised form
16 November 2018
Accepted 21 November 2018
Available online 26 November 2018

Keywords:
Gas emission reduction
Climate change
Energy consumption
Mechatronic systems
Fuzzy logic control
Pierburg actuator

ABSTRACT

China transport energy consumption grows greatly along with dramatically escalated carbon dioxide emissions. Saving energy in transportation is requested for both reducing energy pressure intensity and decreasing relevant emissions. Large scale energy conservation and emission reduction are Chinese automotive industrys' fundamental objectives. This paper addresses a nonlinear hybrid fuzzy based proportional integral derivative (PID) control methodology to reduce the automobile fuel over-consumption and gases over-emission. After introducing the mathematical model of the automobile Pierburg mechatronic actuator of nonlinear character with parameter uncertainties, its angular displacement is controlled via the proposed PID-fuzzy logic control (FLC) approach. The outputs of the PID controller are the entries of the series-connected FLC. The hybrid topology merges the simplicity and robustness advantages of both the classical PID and the FLC methods respectively. The feedback controller, based on FLC technique, is designed to desirably maintain the angular displacement towards their desired reference values with possible least steady state errors. The proper steady state error elimination will lead to considerable gas emission reduction together with improved energy efficiency. Through Matlab/Simulink tools, the numerical simulations significantly illustrate that the hybrid PID-FLC technique can contribute efficiently in ameliorating the system dynamic behavior in presence of parameter uncertainties. The overall system behavioral analysis enhancement and the proposed controller robustness are experimentally validated.

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1. Introduction

The recent interest in automobile energy efficiency enhancement has grown in response to rising fuel costs and the relevant increased pollution concerns (including climate change and oil spills)(Zhao et al. (2014); Wu and Huo (2014); Wang et al. (2014)). Globally, transportation is a considerable energy consumer and green house gas (GHG) emitter (Zhao et al. (2014); Wu and Huo (2014); Lin and Xie (2013)). Road transportation becomes among the largest oil consumers and emission sources in China (Gonzalez-Gil et al. (2013); Huaman and Jun (2014); Lo (2014)). Road transport emits around 8% of China total energy related GHGs (Gonzalez-Gil et al. (2014); Kumar and Jain (2014); Pietzcker et al. (2014)). The global car sales of the world increased year by year, and the annual growth rate average from 2012 to 2016 was 3.39%. In 2016, global car sales exceeded 90 million vehicles, and the global car sales expected to exceed 97 million vehicles in 2017. China was the top car producer in 2016 with a production of 28.12 million units. The automobile production and sales by year are shown in Fig. 1.

From 2012 to 2017, the worldwide Automobile production annual growth rate percentage becomes 3.69, 2.78, 1.11, 4.63 and 3.04% respectively. This have shown an annual rise average percentage of 3.05%. The annual Automobile sales increase by 4.24, 3.19, 1.52, 4.66 and 3.39% respectively from 2012 to 2017 (with an average of 3.40%) (ZhiYan Consulting Group (2017)). In the last three decades, the tremendous annual rate of Chinese economic growth has reached about 10% of annual growth in the gross domestic product (GDP) (Zhao et al. (2014); Shin et al. (2013); Lee and Zhong (2014)). Due to the rapid economic development in China, the great challenge of facing fuel over-consumption and gases over-emission becomes a must. Consequently, many research studies for

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https://doi.org/10.1016/j.jclepro.2018.11.193
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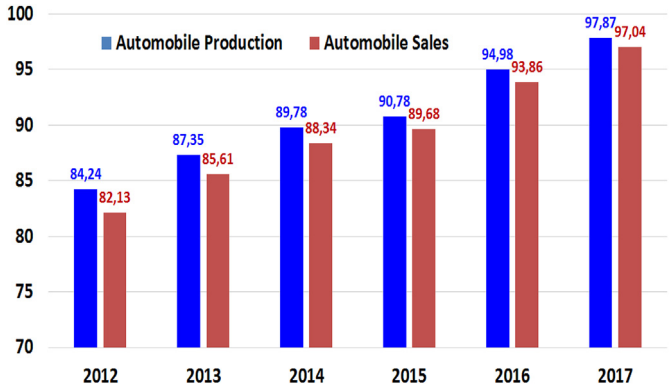

Fig. 1. The automobile production and sales by year.

tackling these problems have been performed (Cipriani et al. (2014); Hung et al. (2014); Hannan et al. (2014)). Electric vehicle (EV) development in China are an option to eliminate the dramatically increasing energy demand from road transport (Wu and Huo (2014); Harris and Webber (2014); Falahi et al. (2013)). Besides the use of hybrid electric vehicle (HEV), the Chinese automotive industry moves on the development of modern vehicles with improved energy efficiency alongside with proposing alternative-fuel (or hydrogen-based) vehicles (Wu and Huo (2014); Falahi et al. (2013); Cipriani et al. (2014)). To promote energy conservation and emission reduction, China latest policy plan has adopted three strategies (Zhao et al. (2014); Falahi et al. (2013)): (i) enhancing the legal system regarding ecological civilization, (ii) providing price and taxation policies with new regulations for stimulus, and (iii) improving the development of environmental markets (Zhao et al. (2014)). Numerous papers have addressed the HEV incorporation for zero and low-carbon emissions solutions (Shen et al. (2017); Meng et al. (2017); Lin and Benjamin (2017)).

The mechatronic actuators, responsible for controlling the air flow circulating around the engine, are largely used in internal combustion engines (ICE). The efficient control of such actuator will positively improve the engine performance. The ageing of vehicles causes gradual deterioration of the vehicle mechanical system performance. Precisely, the parameter variations of the air loop components may change the air-fuel mixture characteristics. These undesired variations may negatively affect the engine efficiency and increase the GHG emissions. The design of both/either robust and/or adaptive controller(s) to cope with parameter variations and uncertainties becomes mandatory. The fuzzy logic control (FLC) technique, the proposed intelligent controller based on the fuzzy set theory and the fuzzy linguistic variables, can be considered a signification option against parameter variations and uncertainties owing to the different accompanied advantages compared to conventional control systems such as (Shaw (1998)):

i FLC is not a knowledge based model technique. Therefore, no need to the system model for the proper task;
ii FLC is robust regardless of the parameters variation.

However, because of the lack of the integral action, the steady-state errors is the main drawback of the FLC to deal with.

For reducing the fuel over-consumption and relevant gases emission rise, the original design of the PID-FLC is designed to control the angular displacement of the automobile mechatronic actuator. Because of the vehicle's actuator nonlinear behavior accompanied with parameters uncertainties, the steady state error in the angular displacement will cause undesired fuel over-consumption and emissions.

This paper fundamental contribution is the innovative PID-FLC controller topology merging both classical PID and the FLC controllers advantages such as simple implementation and adaptive/robust performance respectively. Thus, the improved angular displacement precision leads to enhanced energy efficiency. Different from other fuzzy based-PID controllers, the proposed PID controller is situated before the FLC and provides this latter with its inputs. The mathematical and the numerical analysis illustrate the efficiency of the novel PID-FLC towards enhancing the dynamic performance of the overall system. The experimental results exhibit the system adequate dynamic behavior while employing the PID-FLC topology. Finally, the proposed controller robustness against the resistance variation/uncertainty is exhibited. Towards reaching the original experimental results while applying the proposed PID-FLC controller to the vehicle's mechatronic actuator for enhancing its dynamic behavior and reducing the consequent undesired CO_2 emissions, the successive methodological steps are depicted in Fig. 2.

This article is organized as follows: Section 2 gives a comprehensive overview through the different research performed in the transport sector for reducing the gas emissions. Section 3 highlights the importance and the necessity of a robust control for improving the energy efficiency. Section 4 presents briefly the Pierburg mechatronic actuator. The proposed PID-FLC structure is exhibited in Section 5. In Section 6, experimentation result of the PID-FLC is presented. Finally, Section 7 concludes this work and draws the relevant perspectives.

2. Literature review

With the recent rapid vehicle number growth-rate, particularly private cars, the transport sector has substantially contributed in undesired increasing of fossil fuel consumption and CO_2 emissions (Chiara and Pellicelli (2016); Cruz and Katz-Gerro (2016); He et al. (2014)). Different studies and researches have been performed seeking for probable potential specially in China (Li et al. (2017); Duan et al. (2015); Xu and Lin (2015)).

Chiara and Pellicelli (2016) have presented a global analysis of the recent and consolidated sustainable transport issues particularly those relevant to energy consumption of road vehicles to satisfy the modern aspirations of the industrialized society. From the analysis, the independency in transport should be developed through both efficiency and alternative energy because of the environmental constraints. In addition, rechargeable hybrid electric vehicles (R-HEV) have to be developed with the aim of reducing the fuel consumption (Chiara and Pellicelli (2016)). Cruz and Katz-Gerro (2016) have focused on transport sector as the major participant in CO_2 emissions and the consequent climate change issues. The authors have analyzed the transport practices from the supplier perspective (Cruz and Katz-Gerro (2016)). He et al. (2017) have proposed a replacement purchase decision model in which the trade-in and subsidy have been provided for vehicle owners to replace their old conventional fuel-powered vehicles with HEVs (He et al. (2014)).

Furthermore, Shen et al. (2017) have analyzed the location and relocation patterns of pollution-intensive industries (PIIs) in Guangdong province, China from 2000 to 2013 to evaluate the role of environmental regulation (ER) applied on PIIs (Shen et al. (2017)). Lin and Benjamin (2017) have examined the impact of capita gross domestic product (GDP) per, energy intensity (EI), carbon intensity (CI) and total population on carbon dioxide emissions in China transport industry from 1980 to 2010 (Lin and Benjamin (2017)). Li et al. (2017) have investigated the effect of the environmental regulation on traffic and transportation industry

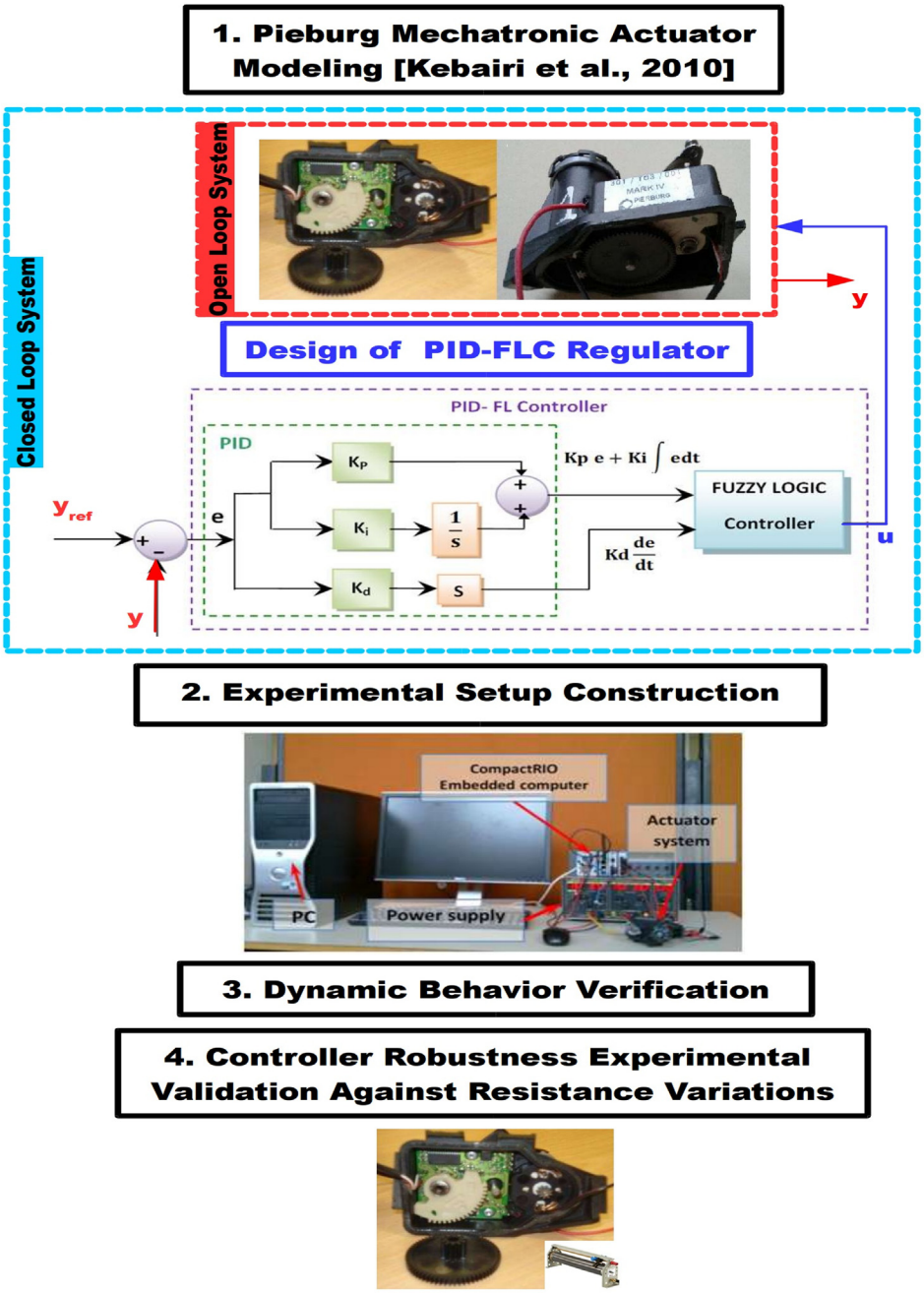

Fig. 2. Methodological steps for the mechantronic actuator research study.

measuring total factor productivity under the general intensity of regulation and strict regulation from 2000 to 2010 (Li et al. (2017)). Duan et al. (2015) have characterized China transport service sector using national official statistical data. The life cycle assessment approach has been used for determining the percentages of CO_2 emissions generated at national level and the relevant transport service sector contribution. In case of the transport service sector, the results have shown that CO_2 emissions has rapidly increased over the past few decades (i.e. estimated to about 3184 million tons in 2012). Additionally, the road sector largely results in transport emissions. Light duty trucks participation in such emissions exceeded 70% (Duan et al. (2015)). Xu and Lin (2015) have studied the CO_2 emissions key influencing factors in the transport sector in China from 2000 to 2012. The estimation results have shown that urbanization increases the CO_2 emissions level alongside with the use of the private electric and hybrid vehicles. In addition, energy efficiency improvement has positively affected on the CO_2 emission amount thanks to the different scale of transportation ownership and the related fast technological progress (Xu and Lin (2015)).

The proposed PID-FLC approach, that combines both the traditional PID control with the FL control algorithm, has been applied in several fields (Li (1998)). The author, in(Li (1998)), has designed a hybrid FL proportional plus classical integral derivative structure (fuzzy P + ID) in incremental manner. In (Ahn and Truong (2009)), fuzzy PID controller online tuned based on a robust extended Kalman filter has been presented. In(Wen et al. (2009)), the

intelligent PID-FLC has been developed for Translation Meshing Motor (TMM) drive system.

The major contribution of this paper is to ensure a specific desired performance by developing a PID-FLC controller which is robust against parameter uncertainties and variations. The nonlinear mechanical system under study, the Pierburg actuator, is mainly affected by parameter uncertainties. Thus, for such automotive actuators, no accurate model is known. According to the authors' best knowledge, the proposed PID-FLC controller is the first attempt for the control of the Pierburg mechatronic actuator for automobile. The PID controller output is used as an input for the FLC. The derivative gain is the second FLC input. This latter deals with the error variation. Through the numerical analysis, the proposed PID-FLC controller provides adequate dynamic performance and robustness even while considering parameter uncertainties. The absence of the accurate system model and the presence of the steady-state error observed with classical FLC controllers are overcame. The overall system performance with the proposed PID-FLC is enhanced and the additional tuning parameters are introduced allowing having an adaptive scale factors K_p, K_i and K_d. The experimental validation of the theoretical hypothesis/analysis and the relevant numerical simulations is accomplished by the authors in the Federation of Research of Fuel Cells (FCLAB), France.

3. Energy assessment

The increased development of automobile industry results in different problems. The more obvious consequences of a vehicle fleet rapid growth are the negative impacts on environment and energy. Although China is the second worldwide largest oil consumer, it has a limited oil reserve (Yan and Crookes (2007)). The Chinese transportation rapid growth rate results in increasing the oil needs. Therefore, the road vehicles have become one of the major oil consumers and emissions. So far, China faces difficulties in dealing with decreasing the energy consumption despite the technology advancements. In China, the average emission levels of vehicles are higher than those in other developed countries. In China, the vehicles are of relatively lower advanced technology, reduced fuel quality and less stringent regulations. With the vehicle number higher increase rates, the problem of energy increases faster. Hence, the future of the Chinese automotive industry should mainly focus on both enhancing the energy efficiency and developing the new-era-technology of hybrid vehicles.

The use of fuzzy logic, as one the artificial intelligence applications, has been largely witnessed through the recent researches in both EVs and HEVs. Johanyak (2015) has designed the FLC model for series HEVs for maintaining constant State Of Charge (SOC) value and to force this latter to follow specific desired behavior. The author has considered the cost function based on fuel and pollution. The proposed model has enabled reaching an optimized equilibrium for the reliable SOC behavior function and the cost (Johanyak (2015)). Kumar et al. (2016) have proposed the speed control scheme for HEVs of highly nonlinear character with controlled electronic throttle system. The PD primary control and the secondary PI control have been used in a cascaded control loop. The fractional order fuzzy PI and PD have provided enhanced results and an adequate robustness under uncertainties (Kumar et al. (2016)). Kraa et al. (2014) have presented the adaptive fuzzy logic hybridized with a maximum control structure for the adaptive operation mode for EVs. The dynamic economic and equilibrium ones have been considered. The robustness of motor drives and 10% save in the state of charge consumption have been verified (Kraa et al. (2014)). Fernandes has studied the energy efficiency control strategy for EVs equipped with continuous transmission variable. The proposed fuzzy controller acts directly on the ratio of the continuous transmission variable system considering different routes for the vehicle (Fernandes (2016)). Rastellia et al. have modeled the fuzzy logic for the autonomous vehicle's steering control inside the roundabout. The cascade structure of both lateral control and parametric trajectory has been considered. Satisfactory results have been attained for different speed profiles (Rastellia and Penas (2015)).

Although the interest of using FLC in both EVs and HEVs, seldom researchers has considered the PID-FLC for enhancing the dynamic behavior of the Pierburg mechatronic actuator with aim of enhancing the relevant energy efficiency and gas emissions. Therefore, the originality in this paper is proposing the new PID-FLC control technology of a Pierburg mechatronic actuator to improve the energy efficiency. The actuator is intergraded into several diesel engine as shown in Fig. 3. If the actuator control is not robust and/or there is a steady state error with the control reference, undesired over-consumption and over-emission will result. The integrated Pierburg mechatronic actuator is placed after the throttle valve and before the combustion chamber for the adjustment of the attached component to manage the air flow towards the cylinder. The amount of air entering to the cylinder is regulated and consequently the characteristics of air-fuel mixture are influenced.

The ageing of vehicles causes a system parameter variations which changes its dynamics and reduces its performance. Fig. 4 illustrates the parameter uncertainty influence of the Pierburg actuator. In Fig. 4, the influence of the motor resistance variations is indicated through adding a series external resistor. Such variation affects the system transient and steady state responses. Accordingly, the development of a robust control is mandatory to ensure an enhanced system operation. To overcome this problem, a PID-FLC design is proposed.

To highlight the importance of this technology for the energy efficiency, the authors have performed the energy study for the car population of 2010. To determine car energy consumption, three different important factors are considered: (VP, VMT and FE) that refer to (the Vehicle Population, the mean Vehicle Mileage Traveled, and the vehicle Fuel Economy) respectively. Thus (He et al. (2005)):

$$FC = VP*VMT*FE^{-1}*FD \quad (1)$$

where FC stands for the fuel consumption (in million tons), VP is in million units, VMT is in thousand kilometers, FE is the average value of on-road fuel economy (km/l), FD is the fuel density (kg/l). According to China's State Statistical Bureau, by the end of 2010, the total number of vehicles civilian use is about 40.29 million. For VMT, according to the Annual Reports of Urban Road Transport Development realized by urban transport planning institutes and surveys conducted by universities (Huo (2005); Wang et al. (2006)), in cities, the annual VMT was about 24 000–27 000 km in the past few years. The authors in (He et al. (2005)) and (Wang et al. (2006)) have stated 11.3 km/l as the cars on-road fuel economy average value measured under the optimal speed. The fuel density of No.93 gasoline (the common used in China) is about 0.725 kg/l. Hence, the fuel consumption for 2010 is 64.624 million tons.

In China, National Standard III norm, equivalent to the standard Euro III, enter into service on July 1st, 2007. Plans for Euro IV norms were considered in 2010. Beijing has adopted on January 1st, 2008) the Euro IV standard as the first city in mainland China (Zhang et al. (2010)). Thus, the Euro IV standard is considered since 2010. According to the Euro IV, for passenger cars, the emission of CO is 1 g/km and that of NO_x is 0.8 g/km. The average emission of CO_2 is 160 g/km. Hence, for the emissions for 2010 were:CO: 1.007 million tons, NO_x: 0.806 million tons, CO_2: 161.16 million tons.

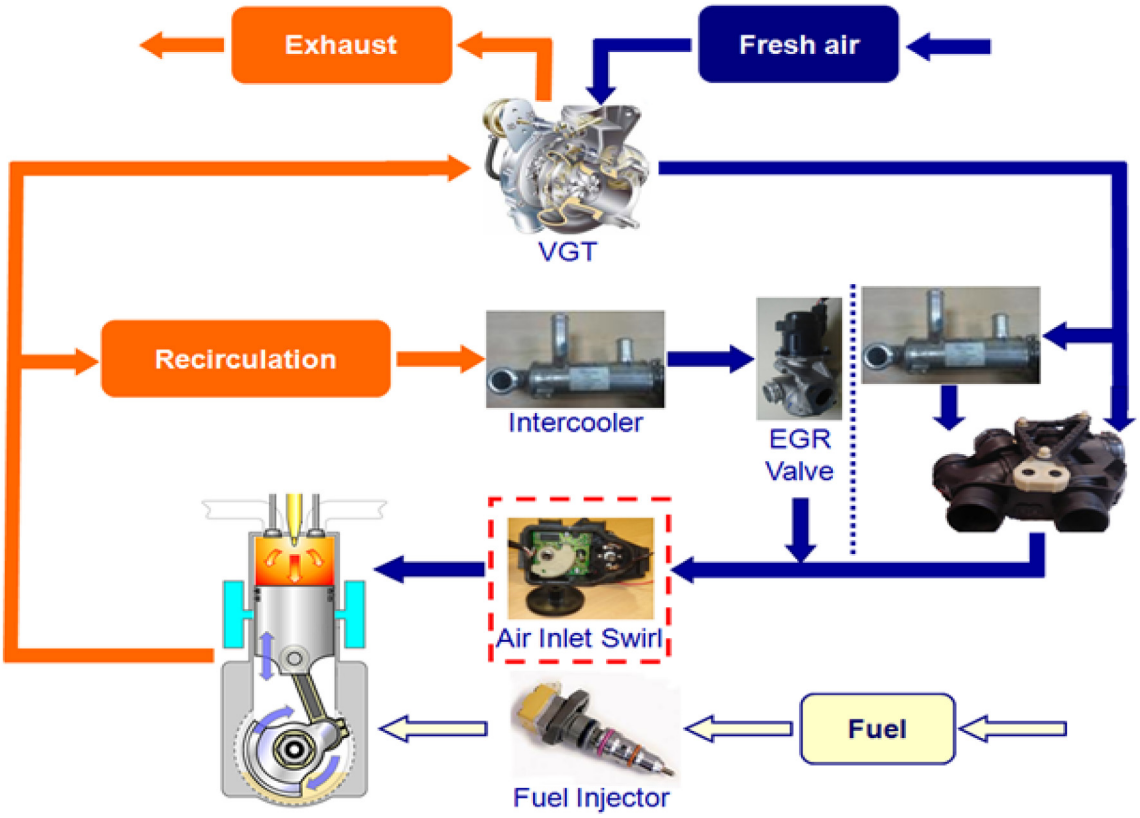

Fig. 3. The location of the Pierburg mechatronic actuator in some diesel engine (Cai et al. (2011)).

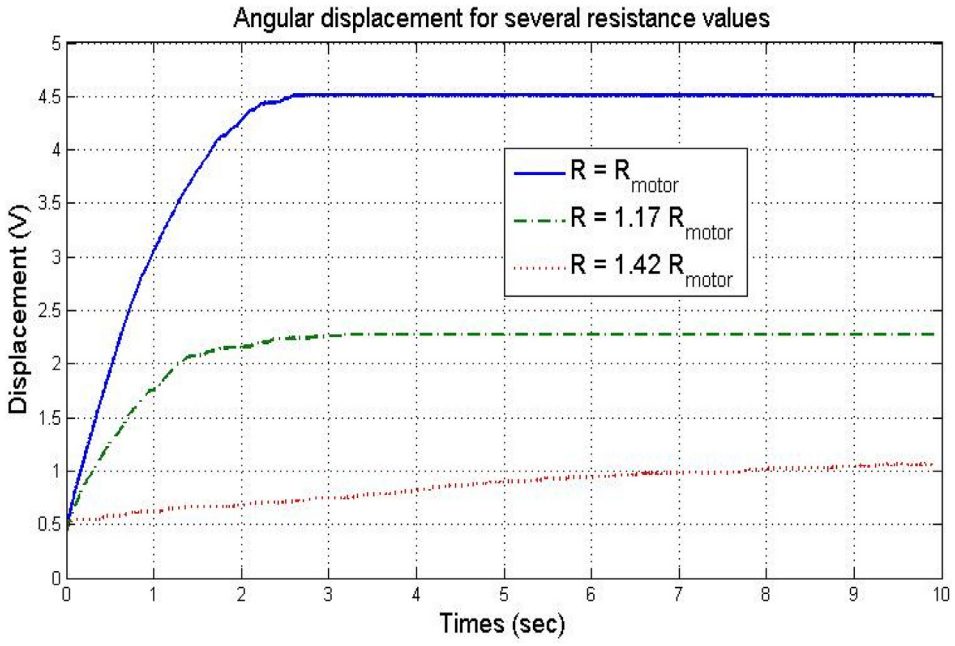

Fig. 4. Experimentation on parameter variation effects.

It is assumed[1] that 5% steady state errors of the Pierburg mechatronic actuator control will lead to 2% of an overconsumption and over emission which means that if the steady state error could be eliminated. For 2010, car fuel consumption could be reduced of about 1.3 million tons. And the car emission of China could be also

[1] French car manufacturers assure that a steady state error causes an overconsumption of fuel and over emission of gazes. No accurate value of this overconsumption can be calculated but according to some car manufacturer engineers this value is realistic.

consequently reduced: CO: 0.02 million tons, NO_x: 0.016 million tons, CO_2: 3.2 million tons. Hence, an advanced control technology for the engine actuator which could achieve good control performance is necessary.

4. The automobile mechatronic actuator

The studied mechatronic actuator contains a Hall Effect Sensor (HES). The angular displacement is detected by the integrated HES using a voltage signal. This actuator is constituted by a DC motor, an integrated control electronic circuit, a two-stage gear and a helical spring attached to the adjustment shaft as shown in Fig. 5. The integrated electronic circuit controls the DC motor towards the desired position. The produced mechanical power is transmitted to the adjustment shaft via the gear. The adjustment shaft angle, α, is mechanically limited between (α_{min} and α_{max}) that correspond to (0° and 90°) respectively (Kebairi et al. (2010); Cai et al. (2010)). The DC motor duty cycle controls the adjustment shaft angle value determined by the HES. The role of the helical spring is returning the adjustment shaft to the initial position α_{min}, when the DC motor duty cycle is zero. Two mechanical stoppers are considered to maintain the value of α within the limits $[\alpha_{min}, \alpha_{max}]$. The integrated electronic control card is disconnected allowing the control of the actuator throw a computer and Labview software.

Because of the spring pre-compression and the friction forces besides the gear system, this actuator is considered as a highly nonlinear system. There is no known analytical model for this system so far. Even car manufacturers use a kind of lookup tables for the simulation purpose. In addition, the actuator has time-variant characteristics. Thus, the model parameters are of considerable uncertain. As there is no defined accurate analytical model for such system, FL approaches can be considered as ideal candidate models for controlling these nonlinear uncertain systems.

5. Design of PID-FLC regulators

5.1. Fuzzy logic control architecture

In FLC approach, the defined rules are resolved into a single-output value to determine the "crisp output" as a defuzzification process. Simplified reasoning method, which is regarded as one modified centroid of area method is a defuzzification method as well (Lee (1990a, b)). The center points of the output fuzzy sets and weighted mean of input membership value are used for determining the crisp output. The output expression is given by weighted mean of input memberships and output values (Sandhu et al. (1996)):

$$u = \frac{\sum_{n=1}^{\sharp\ of\ Rules} \mu_{rulen} U_{rulen}}{\sum_{n=1}^{\sharp\ of\ Rules} \mu_{rulen}} \quad (2)$$

where μ_{rulen} refers to the input membership degree determined by multiplying the membership degree of error input for the assigned fuzzy subset with the change membership degree in error input related to the change in error fuzzy subset (μ_{rulen}= [membership degree of error in A_j] * [membership degree of change in error in B_k]). The center value, U_{rulen}, is the output for rule n. The membership μ_{A_j} for A_j is illustrated in Fig. 6.

One linear approximation of most FLC is given by defuzzification, constraints for the fuzzification and an FLC knowledge base, such as:

Constraint 1: Triangular membership functions are used in the fuzzification process.
Constraint 2: The fuzzy set width extends to the maximum value of each adjacent fuzzy set and vice versa (see Fig. 6). Over the

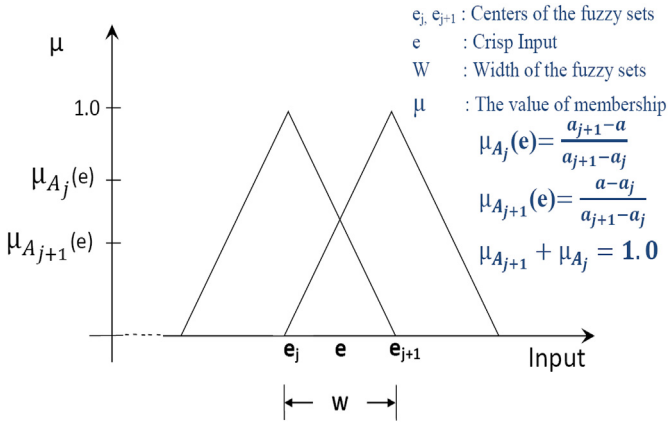

Fig. 6. Two membership functions for the variable e in the universe of discourse (Cai et al. (2011)).

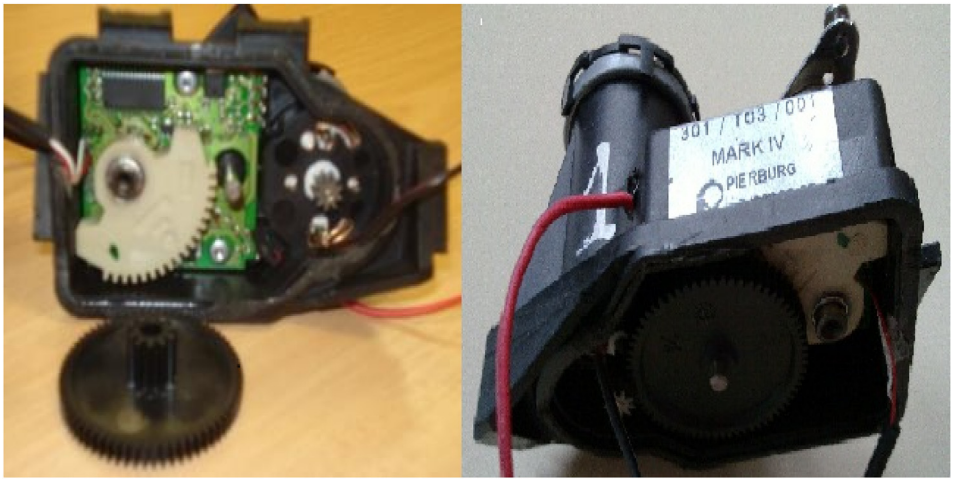

Fig. 5. The Pierburg mechatronic actuator (Cai et al. (2011)).

interval between two adjacent sets, the membership values summation equals to one. Consequently, at any instant, the sum of all membership values over the universe of discourse for the control variable becomes one.

Constraint 3: The modified center of area calculation, used as the defuzzification method, is equivalent to obtaining a weighted mean of all possible output values. Hence, this component is linear as well.

The FLC is basically a linguistic expression of the desired control action. Then, the purpose of defuzzification processes and quantitate expression of the fuzzification used for translating the "English", which is similar to a mathematical form, is to deduce an output function for the FLC. Equations used in fuzzification process aim at returning membership quantity for various crisp inputs. For defuzzification, output expression of the FLC is given by substituting these membership functions into equations.

There are two important input variables for the FLC: the error and the error variation inputs respectively. The error input is the difference between the desired and actual values. The error variation input is the difference between current and previous errors divided by the time interval. For both the error and its variation fuzzy sets in Fig. 6, there is a membership in two fuzzy sets for each input. For the error values between e_j and e_{j+l}, the fuzzy sets (E_J and E_{J+1}) become active. Thus, the representation in Fig. 6 regarding the membership in E_J and E_{J+1} are:

$$\begin{cases} \mu_{E_J}(e) = \dfrac{e_{j+1} - e}{e_{j+1} - e_j} \\ \mu_{E_{J+1}}(e) = \dfrac{e - e_j}{e_{j+1} - e_j} \end{cases} \tag{3}$$

For the error variation input Δe between Δe_k and Δe_{k+1}, the membership function in ΔE_K and ΔE_{K+1} are analogously:

$$\begin{cases} \mu_{\Delta E_K}(\Delta e) = \dfrac{\Delta e_{k+1} - \Delta e}{\Delta e_{k+1} - \Delta e_k} \\ \mu_{\Delta E_{K+1}}(\Delta e) = \dfrac{\Delta e - \Delta e_{k+1}}{\Delta e_{k+1} - \Delta e_k} \end{cases} \tag{4}$$

Obviously, the total of memberships deduced by the set of Eq. (3) and the same for Eq. (4) respectively is 1. For the four applicable rules listed in Table 1, the other two control variables, error and error variation, with two active sets.

Applying the modified expression (2) for four control rules determines the crisp output control action given by:

$$u = \frac{\sum_{i=1}^{4} \mu_i U_i}{\sum_{n=1}^{4} \mu_i} \tag{5}$$

where μ_i refers to the input membership value obtained through multiplying the input membership values of both the error in the error fuzzy subset of the i^{th} rule and the corresponding error variation for the change in error fuzzy subset. U_i is defined as the center value of the output fuzzy set for the i^{th} rule. The expressions for μ_i and the output values U_i are listed in Table 2.Where μ_i is regarded as input membership degree calculated by multiplying the membership degree error variation input for the corresponding error variation fuzzy subset and the membership degree of error input in given error fuzzy subset according to the i^{th} rule. U_i represents the center value of output fuzzy set for the i^{th} rule. Expressions for output values U_i and μ_i are listed in Table 2.

Substitute these above expressions into equation (5) to reach:

$$u = \frac{\mu_1 * U_{J,K} + \mu_2 * U_{J+1} + \mu_3 * U_{J,K+1} + \mu_4 * U_{J+1,K+1}}{\mu_1 + \mu_2 + \mu_3 + \mu_4} \tag{6}$$

The final expression of FLC output equation is deduced by rearranging the terms and removing the common denominator:

$$\begin{aligned} u = {} & e^* \frac{\Delta e_k (U_{J,K+1} - U_{J+1,K+1}) + \Delta e_{k+1} (U_{J+1,K} - U_{J,K})}{(e_{j+1} - e_j)(\Delta e_{k+1} - \Delta e_k)} + \\ & \Delta e^* \frac{e_{j+1} (U_{J,K+1} - U_{J,K}) + e_j (U_{J+1,K} - U_{J+1,K+1})}{(e_{j+1} - e_j)(\Delta e_{k+1} - \Delta e_k)} + \\ & (e^* \Delta e) \frac{(U_{J,K} - U_{J,K+1}) + (U_{J+1,K+1} - U_{J+1,K})}{(e_{j+1} - e_j)(\Delta e_{k+1} - \Delta e_k)} + \\ & \frac{e_{j+1} (\Delta e_{k+1} U_{J,K} - \Delta e_k U_{J,K+1}) + e_j (\Delta e_k U_{J+1,K+1} - \Delta e_{k+1} U_{J+1,K})}{(e_{j+1} - e_j)(\Delta e_{k+1} - \Delta e_k)} \end{aligned} \tag{7}$$

Authors have discussed this expression and deduced an appropriate numerical approach for FLC output (Sandhu et al. (1996)). FLC output, obtained from equation (7), expresses the error and its variation that relies on a mathematical term equivalent to the product of both. Nevertheless, this term is negligible because both e and Δe are considerably small. Hence, their product is tiny. The input and output sets are fixed for the specified operating point. The variable values are the error variation and the crisp error. Obviously, the coefficients of both e and Δe as well as the last term in equation (7) are constant for such specific operating point. Compared to the classical PD output, the coefficients of Δe and e can be defined as the derivative and proportional gains (K_d and K_p respectively). Equation (7) describes the variable coefficients (unlike the case of the classical controller). However, their change depend on the variation in the operating point that impacts the error and its derivative. This constitutes an adaptive PD controller. Hence, the FLC equation becomes:

$$u = K_{p-eff} * err + K_{d-eff} * \frac{derr}{dt} + Constant \tag{8}$$

where err and $\frac{derr}{dt}$ are the error and its variation respectively. Both K_{p-eff} and K_{d-eff} are the proportional and the derivative gains respectively. K_{p-eff} depends on the error and K_{d-eff} changes with the error variation. Therefore, this expression is equivalent to the classical PD controller. However, the gains K_{p-eff} and K_{d-eff} are not constant. Their values should be updated based on the operation point which changes with the error and its variation. Therefore, the design of an adaptive controller becomes mandatory.

Table 1
Four applicable rules of fuzzy logic.

$R_{J,K}$:	if e is E_J	and Δe is ΔE_K,	then U is $U_{J,K}$
$R_{J+1,K}$:	if e is E_{J+1}	and Δe is ΔE_K,	then U is $U_{J+1,K}$
$R_{J,K+1}$:	if e is E_J	and Δe is ΔE_{K+1},	then U is $U_{J,K+1}$
$R_{J+1,K+1}$:	if e is E_{J+1}	and Δe is ΔE_{K+1},	then U is $U_{J+1,K+1}$

5.2. The structure of the designed PID-FLC

The proposed novel PID-FLC structure is developed as depicted in Fig. 7. The PID fuzzy logic controller and the automobile mechatronic actuator are the main system components.

The PID-FLC consists of a classical FLC and a PID controller. Most of the developed fuzzy controllers require two inputs (the error and

Table 2
The formulation of μ_i and.U_i

$R_{J,K}$:	$\mu_1 = \frac{e_{j+1}-e}{e_{j+1}-e_j} * \frac{\Delta e_{k+1}-\Delta e}{\Delta e_{k+1}-\Delta e_k}$,	$U_1 = U_{J,K}$
$R_{J+1,K}$:	$\mu_2 = \frac{e-e_j}{e_{j+1}-e_j} * \frac{\Delta e_{k+1}-\Delta e}{\Delta e_{k+1}-\Delta e_k}$,	$U_2 = U_{J+1,K}$
$R_{J,K+1}$:	$\mu_3 = \frac{e_{j+1}-e}{e_{j+1}-e_j} * \frac{\Delta e-\Delta e_{k+1}}{\Delta e_{k+1}-\Delta e_k}$,	$U_3 = U_{J,K+1}$
$R_{J+1,K+1}$:	$\mu_4 = \frac{e-e_j}{e_{j+1}-e_j} * \frac{\Delta e-\Delta e_{k+1}}{\Delta e_{k+1}-\Delta e_k}$,	$U_4 = U_{J+1,K+1}$

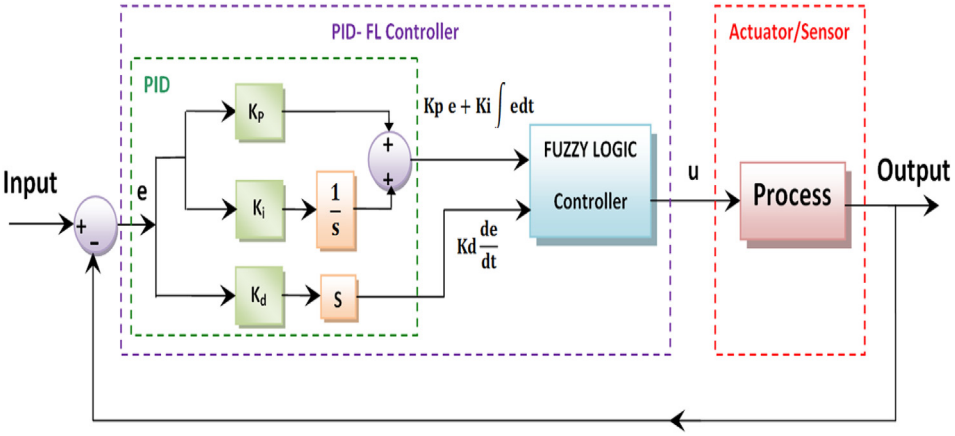

Fig. 7. Block diagram of the proposed control architecture.

its variation). The proposed FLC has a special input, which represents PI controller input as shown as in Fig. 7. It is the sum of the error and its integration: $K_p e + K_i \int edt$. Both K_p and K_i respectively refer to the proportional and integral gains.

The error derivative $\frac{de}{dt}$ is the second input of proposed FLC. In the classical PID controller, the derivative gain K_d restrains the process error's change rate that accelerates or slows down the dynamics of the controller output. Therefore, the derivative gain, K_d, can affect on improving the transient response, reducing the overshoot and increasing the system stability. Fig. 7 shows how the derivative gain K_d is added in the proposed controller as a FLC input.

Additional important control objective while using the mechanical actuator is to significantly reduce (or to cancel) the steady state error. To achieve this goal, the authors have proposed the addition of an integral action as an extra FLC input.

The control output u refers to the actual voltage value, generated by the controller and applied to the actuator. The designed PID-FLC aims at regulating the mechanical actuator's angular displacement for attaining adequate dynamic performance free of steady state errors. Therefore, the inputs of the proposed PID-FLC are:

$$err = K_p e + K_i \int edt \tag{9}$$

$$\frac{derr}{dt} = K_d \frac{de}{dt} \tag{10}$$

From equation (8) obtained in (Sandhu et al. (1996)), and using equations (9) and (10) respectively, the PID-FLC output can be expressed as:

$$u = K_{p-eff} K_p e + K_{p-eff} K_i \int edt + K_{d-eff} K_d \frac{de}{dt} + Cst \tag{11}$$

where Cst is a constant. According to equation (11), the designed PID-FLC is equivalent to an adaptive PID controller with tuned K_p, K_i and K_d gains. Compared to the classical FLC in equation (8), the new term $K_{p-eff} K_i \int edt$ is added to the PID-FLC to positively affects on canceling and/or minimizing the steady state error. Therefore, the proposed PID-FLC is equivalent to an adaptive PID controller where K_{d-eff} and K_{p-eff} are defined by the rules of the FLC and the membership functions. Similar to the PID control, the overall system dynamic performance can be improved by the proper tuning of the gains K_p, K_i and K_d. As the proposed PID-FLC is based on the FLC, the developed controller can conveniently deal with nonlinear systems with uncertain parameters character. Consequently, the proposed PID-FLC is an adequate controller that provides merged advantages of both the PID and Fuzzy logic controllers.

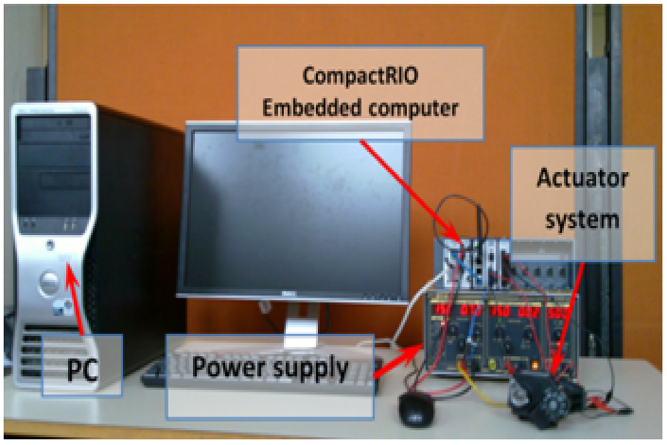

Fig. 8. The experimental setup.

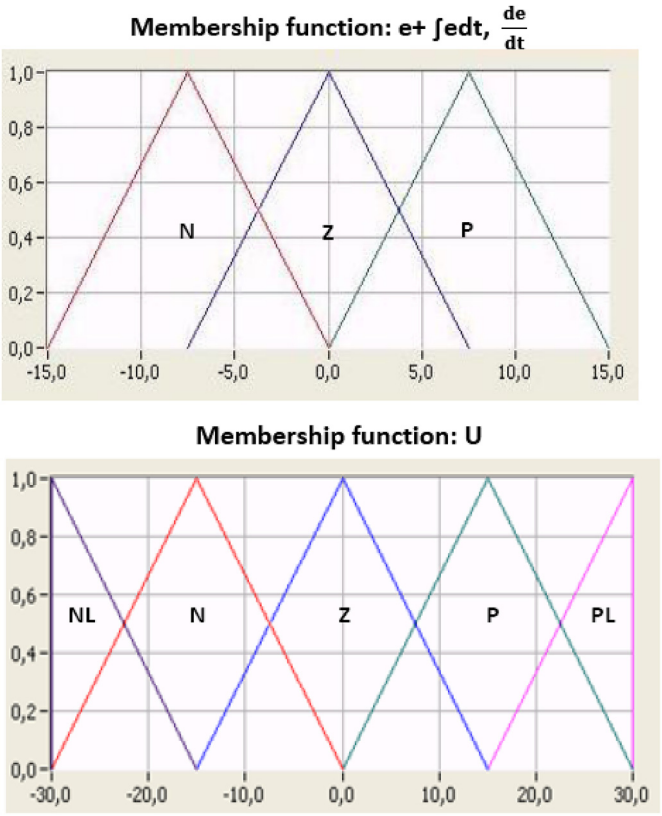

Fig. 9. Membership functions for FLC.

6. Experiment setup result

An experimental setup, developed by the authors in the University of Technology Belfort-Montbeliard, is depicted in Fig. 8. The PID-FLC is programmed using LabVIEW FPGA. The program is executed into an embedded computer (National Instruments CompactRio: NI CRIO-9022). The sampling analog input module, NI 9215, helps the CompactRio both to convert and to receive the analog data of the angular displacement coming from the HES. The system sampling frequency is 40 kHz.

Here, the FL method based mainly on the designer knowledge/experience and linguistic definition, is used instead of the analytic model (Thepsatorn et al. (2006)). To achieve the desired performance, for unknown/known plants, the procedure deals with defining the input and output fuzzy sets and their relationships. Therefore, as for the classic FLC, it becomes mandatory to define the membership functions which represent the fuzzy membership (value between 0 and 1). The inputs and outputs membership functions shape for $(e + \int edt)$, $(\frac{de}{dt})$ and U in the proposed FLC are given in Fig. 9.

The linguistic levels given for all fuzzy variables are: PL: Positive Large, P: Positive, Z: Zero, N: Negative and NL: Negative Large.

The fuzzy rule is based on the FLC main part. The quantitative relationship described by fuzzy rules between variables in linguistic terms. The fuzzy rules are defined in Table 3.

Unlike the typical FLC, the new proposed PID-FLC provides two special inputs presented in equations (9) and (10). In order to attain sufficient dynamic performance, the derivative, integral and proportional positive gains (K_d, K_i and K_p) respectively are added in the PID-FLC under study. These gains are tuned using trial/error owing to the experience of designers. After different tests,[2] the estimated gain values (K_p=3, K_d = 1 and K_i = 0.01) enabled adequate dynamic behavior in the experimental results shown in Fig. 10. Obviously, the steady-state error is around 0 and the overshoot is acceptable in different case studies. Hereby, the robustness of the proposed controller is verified. In the bottom of Fig. 10 illustrates the error between the angular displacement and its reference.

Table 3
Fuzzy rules for the proposed controller.

$\frac{de}{dt}$	$e+\int edt$		
	N	Z	P
N	NL	N	Z
Z	N	Z	P
P	Z	P	PL

The motor resistance variations are performed via connecting a series external variable resistor. To study the proposed controller robustness, Fig. 11 shows the actuator dynamic behavior where the total resistance $R_T = 1.17R_{motor}$ and $R_T = 1.42R_{motor}$ respectively. These experimental results confirms the robustness of the PID-FLC against parameter uncertainties. The capability of the proposed PID-FLC controller to attain significant overall system dynamic performance is ensured. Consequently, enhanced motor efficiency with lower GHG emissions is reached. Still the determination of the optimized values of the proposed PID-FLC gains is a subject of interest through the use of the different meta-heuristic optimization techniques introduced in the literature (Cai et al. (2011); Claude et al. (2017); Becherif et al. (2017a, 2012b,c); Ramadan (2017a,b); Ramadan et al. (2017); Soued et al. (2017); Fathy et al. (2017)).

7. Conclusions and perspectives

With the rapid economic growth in China, fuel consumption and car emissions are rising tremendously related to on-road transportation. In the next two or three decades, this dramatic increase will tend to continue. The reason is that the actual private car ownership level in China is still relatively lower than that in developed economies' countries. Even if it is compared with the world's average level, the result will be similar. China has to face the problems of the fuel compulsion and the emission. More than other countries, the Chinese automotive industry has to bring considerable attention dealing with reducing energy consumption and emission besides overcoming the gap with modern automotive manufacturers.

For improving the energy efficiency of the thermal engines, the new designed controller PID-FLC has been employed to attain adequate Pierburg mechatronic actuator angular displacement control. The idea behind the proposed controller is to merge the FLC with the PI controller to reduce the steady state error and/or the overshoot. In addition, the classical error time derivative used as a second FLC input provides an additional tuning parameter through the multiplication by the derivative gain of the PID.

The proposed PID-FLC exhibits adequate performance of faster time response, reduced steady-state error and overshoot. The robustness of the studies PID-FLC is verified in presence of parameter uncertainties. In general, it is difficult to get rid of the steady-state error with the reason that the integral control is not in the fuzzy control theory. The proposed control structure overcome this main drawback. The experimental results illustrate the enhanced stability of the overall controlled system via the proposed PID-FLC controller. The realized tests confirms the capability of the PID-FLC to guarantee the desired displacement while considering

[2] Neither the actuator model nor the parameters is known.

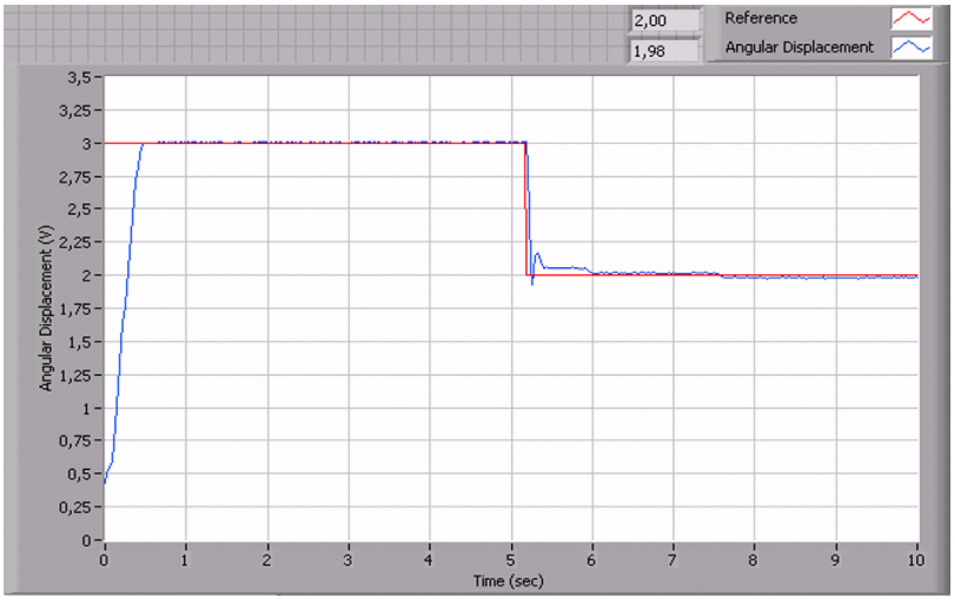

Fig. 10. Experimental result of step time responses with PID-FLC.

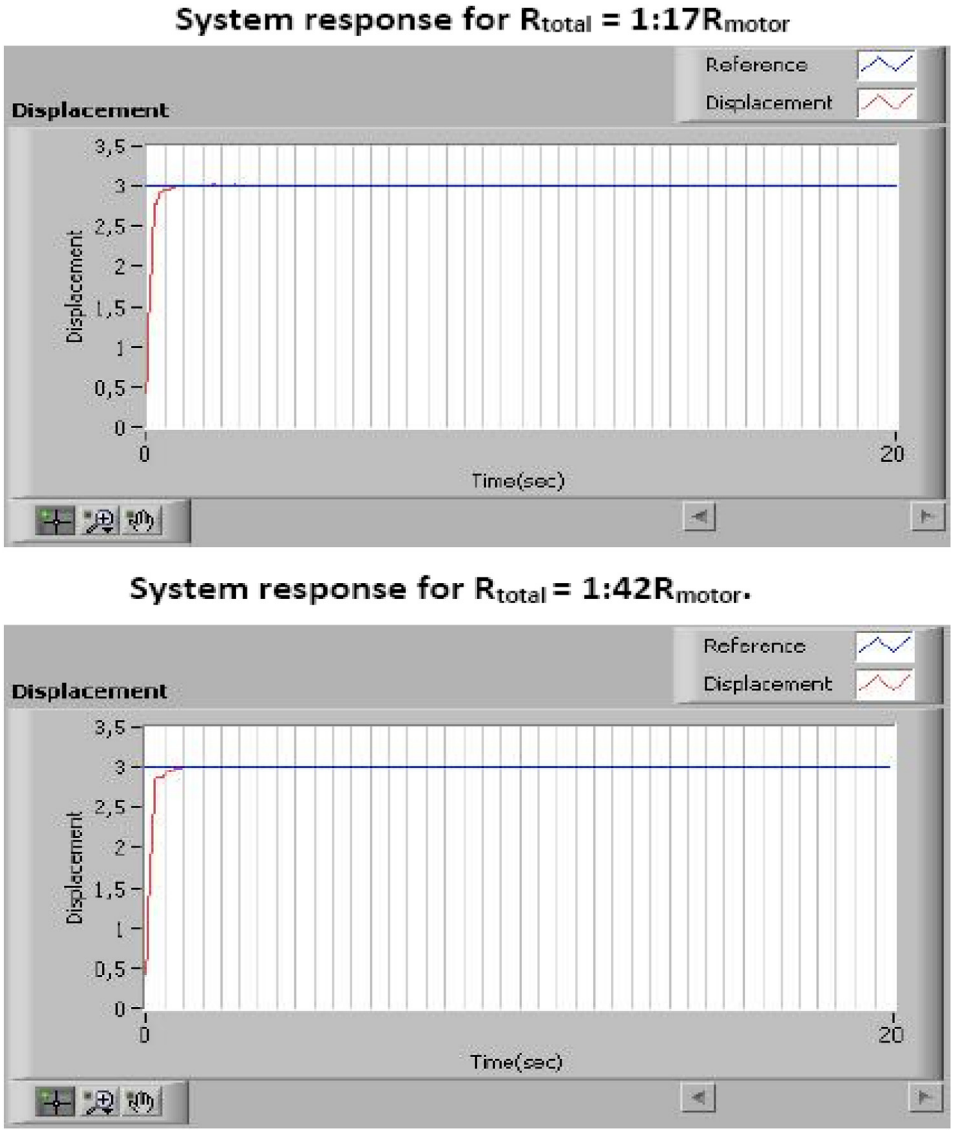

Fig. 11. Robustness evaluation and system responses for various $R_{total} = 1.17R_{motor}$ and $R_{total} = 1.42R_{motor}$.

unexpected parameter variations. Thus, both the desired air-fuel mixture characteristics and the enhanced engine efficiency are reached. In presence of load variation/uncertainty, the proposed Robust PID-FLC is capable of providing acceptable dynamic performance which will positivity affect the vehicles CO_2 emissions. The forthcoming research will mainly focus on designing optimal real time control operation for the Pierburg mechatronic actuator for minimizing the CO_2 emissions of the vehicles.

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